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Estimating UK perennial energy crop supply using farm-scale models with spatially disaggregated data

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Abstract

To achieve the UK Government's aim of expansion in the growth of perennial energy crops requires farmers to select these crops in preference to conventional rotations. Existing studies estimating the total potential resource have either only simplistically considered the farmer decision-making and opportunity costs, for example using an estimate of annual land rental charge; or have not considered spatial variability, for example using representative farm types. This paper attempts to apply a farm-scale modelling approach with spatially specific data to improve understanding of potential perennial energy crop supply. The model main inputs are yield maps for the perennial energy crops, *Miscanthus* and willow grown as short-rotation coppice (SRC), and regional yields for conventional crops. These are used to configure location specific farm-scale models, which optimize for profit maximization with risk aversion. Areas that are unsuitable or unavailable for energy crops, due to environmental or social factors, are constrained from selection. The results are maps of economic supply, assuming a homogenous farm-gate price, allowing supply cost curves for the UK market to be derived. The results show a high degree of regional variation in supply, with different patterns for each energy crop. Using estimates of yields under climate change scenarios suggests that *Miscanthus* supply may increase under future climates while the opposite effect is suggested for SRC willow. The results suggest that SRC willow is only likely to able to supply a small proportion of the anticipated perennial energy crop target, without increases in market prices. *Miscanthus* appears to have greater scope for supply, and its dominance may be amplified over time by the effects of climate change. Finally, the relationship to the demand side of the market is discussed, and work is proposed to investigate the factors impacting how the market as a whole may develop.

Keywords: economics, energy crops, farm-scale modelling, *Miscanthus*, risk & uncertainty, short-rotation coppice, spatial analysis

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Introduction

Increased biomass use is expected to contribute to the UK's target to source 15% of energy from renewable sources by 2020 (DECC, 2009). The UK Biomass Strategy identifies the prospect of part of the required supply coming from a major expansion in UK production of perennial energy crops, potentially using 350 000 ha, an area equivalent of 6.5% of total arable land (DEFRA, 2007). Despite the existence of financial incentives, the area of UK perennial energy crops established has so far been comparatively limited, at around 17 000 ha (RELU, 2009). The low level of uptake is supported by data from Natural England on the areas receiving establishment grants; in the period 2000–2006 a combined area of 8191 ha was given grant support, while in the period 2007–2011 the area was only 1305 ha (Natural England, 2006, 2011).

A number of studies have investigated and modelled the biophysical properties of perennial biomass crops, as well as assessing the optimal spatial locations for production given biophysical constraints (Price *et al.*, 2004; Andersen *et al.*, 2005; Aylott *et al.*, 2008; Richter *et al.*, 2008; Hastings *et al.*, 2009), with other work

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applying environmental and socials constraints (Lovett *et al.*, 2009; Aylott *et al.*, 2010). The supply-side economics of energy crops has been considered using a variety of approaches, perhaps the simplest is accounting for the opportunity costs as using an estimate of annual land rental (Monti *et al.*, 2007; E4tech, 2009; Bauen *et al.*, 2010). Another commonly taken approach is to compare annual gross margins of conventional crops with an equivalent annualized value for the perennial energy crops (Bell *et al.*, 2007; Styles *et al.*, 2008; Turley & Liddle, 2008). Farm-scale economic models have also been used to investigate the potential uptake of perennial energy crops (Sherrington & Moran, 2010). Existing studies into assessing total potential perennial energy crop resource and supply curves appear either to have only simplistically considered the farmer decision-making and opportunity costs, for example using an estimate annual land rental charge; or have not considered spatial variability, for example using representative farm types (Sherrington & Moran, 2010). The importance of increased understanding in this area is apparent by looking at the low levels of uptake to date (RELU, 2009). To increase the understanding of the supply side of this market, an improved estimate of the level of economic supply, how it is geographically distributed, and the supply response to changes in market price are required. This understanding could be used to investigate the potential impact of possible policies on the rate and level of development in the perennial energy crop market.

This study presents the use of a farm-scale modelling approach with spatially specific data to provide an improved understanding of the potential economic perennial energy crop supply from *Miscanthus* (*Miscanthus* × *giganteus*) and short-rotation coppice (SRC) willow (genotype Joruun, *Salix viminalis* L. × *S. viminalis*). The farm-scale model construction and use is summarized, with the source of land-use constraints and yield distribution data presented. The resultant maps of economic supply and supply cost curves for the UK market are given and discussed. The impacts of climate change scenarios on the results are also investigated.

Materials and methods

Overall approach

A farm-scale model was spatially configured for each location within the United Kingdom, using a 1 km^2 grid, representing a homogenous 100 ha farm size. The energy crop yields used predicted yields generated at that spatial resolution (Hastings *et al.*, 2014; Tallis *et al.*, 2013), while the conventional crop yields were estimated from observed mean regional yield data. Areas where energy crop may not be appropriate for social or environmental reasons were excluded from selection (Lovett *et al.*, 2014), as described in the social and environmental constraints in this study. Areas where no demand was predicted for biomass from perennial energy crops (Wang *et al.*, 2014) were also excluded, as described in the demand constraints in this study. Once an optimized farm plan (i.e. based on constrained profit maximization) is available for each location, the results can be extracted to produce maps of likely crop supply distribution, or data extracted to generate supply rates for different geographical areas. Running the analysis for a range of energy crop prices also allows supply curves to be generated, repeated using yields under UKCP09 climate change scenarios (Murphy *et al.*, 2009) to determine the response under these conditions. Figure 1 gives details of the processes involved in spatially configuring the farm-scale model and extracting combined results from its multiple executions.

Farm-scale model

The farm-scale model represents decision-making in an arable farm type, where the optimization criterion represents profit maximization with constant absolute risk aversion. It was initially developed to look at the impact of income variability and risk aversion to the farmer selection of energy crops (Alexander & Moran, 2013). Conventional arable crop activities (winter wheat, winter barley, spring barley, winter oats, oilseed rape, sugar beet, peas, beans and main crop ware potatoes), for multiple fertilizer application rates, plus the two energy crop activities were represented. Constraints were set on land availability and crop rotations. All operations are charged at contract rates, including an allocation for machinery cost and fuel cost. These rates are constant for all locations, any spatial variation in productions costs, e.g. due to soil types, are not represented. Prices, input rates and contractor rates were updated to use data from the SAC farm handbook 2010/11 (SAC, 2010). The resulting non-linear mathematical programme was implemented in GAMS (General Algebraic Modelling Systems) and optimized using the CONOPT3 solver (Brooke *et al.*, 2010).

Energy crop representation. An annual equivalent value approach was used to allow the comparison of the perennial energy crops with the annual gross margins of the conventional crops (Bell *et al.*, 2007; Sherrington & Moran, 2010). Future values were adjusted into 2010 terms using a 6% discount rate, representing an estimate of farmers' cost of capital (Sherrington & Moran, 2010). SRC willow plantations were expected to be harvested every 3 years (Armstrong, 1997). The total lifespan was taken as 21 years, or 7 harvests (Bauen *et al.*, 2010). *Miscanthus* plantations were harvested annually starting in the second year, with a 16 year lifespan (Styles *et al.*, 2008). For a given farm and scenario, the yields were assumed to be constant, with the exception of the first SRC harvest where the yield was reduced to 60% (Kopp, 2001). Prices are taken as farm-gate prices, and assumed constant over the crop lifetime. A 50% establishment grant was included, as per with the Energy Crops Scheme (Natural England, 2009). Fertilizer was taken as only being applied to SRC at planting and after each harvest (Bell *et al.*, 2007). *Miscanthus* does not require significant

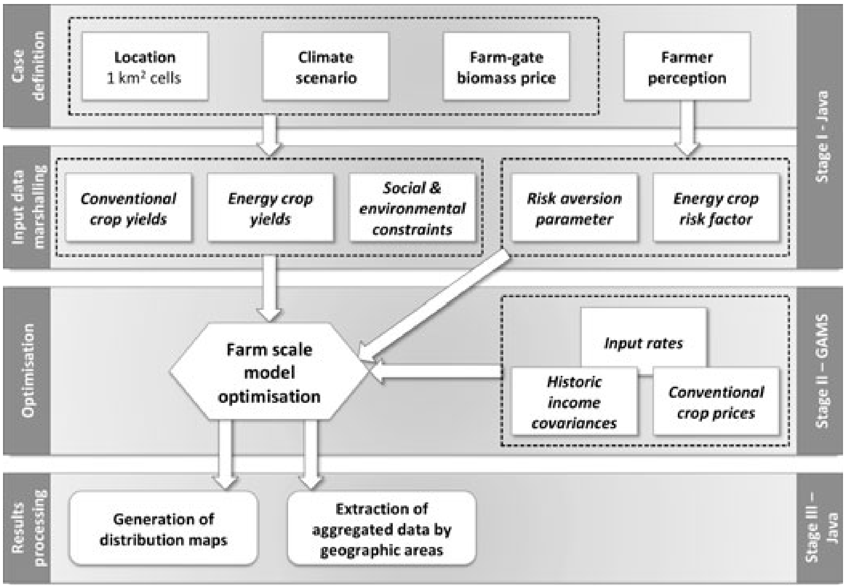

Fig. 1 Flow diagram of process to configure and optimize farm-scale model to generate energy crop supply maps.

fertilizer application as it recycles nutrients, and was taken as 85 kg ha^{-1} N and 45 kg ha^{-1} each of P and K at establishment, and 40 kg ha^{-1} of N assumed after year 5 and 10 (NNFCC, 2010a). Energy crop establishment figures and structure were followed from Bauen *et al.* (2010), adjusted to 2010 terms using the CPI inflation data (ONS, 2011), see Table 1.

Risk model. The portfolio choice rule using expected income-SD was selected in the farm-scale model applied, and can be expressed as:

$$\text{maximize U} = E - \varphi\sigma \tag{1}$$

where: U is the utility; E is the expected income; ϕ, the risk aversion parameter, assuming constant absolute risk aversion; and σ is the SD. The reasons for selecting this approach are examined in (Alexander & Moran), including that the risk aversion parameter is unit-less and comparable to other studies (Hazell & Norton, 1986). It is the key model parameter that cannot be directly set from observation or spatially specific data. As it represents a farmer's view on risk, a range of values would be expected within a set of farmers. Hazell & Norton (1986) cited various researchers imputing risk aversions in the range of 0.5–1.5. In line with these results, a central estimate of ϕ = 1.0 was chosen. Although some studies have found or assumed values slightly outside this range, for example Seman *et al.* (2007) used 1.65; and Brink & McCarl (1978) imputed 0.23. To cover these cases, the behaviour of the model over the range ϕ = 0.0–2.0 was investigated.

Table 1 Rates for energy crops operations

Item	Unit	*Miscanthus*	SRC willow
Establishment Cost	£ ha^{-1}	1949	2183
Establishment Grant	£ ha^{-1}	975	1092
Removal	£ ha^{-1}	109	547
Fixed overhead	£ ha^{-1} yr^{-1}	95	95
Fertilizer	£ ha^{-1} per application	0	27
Harvesting Cost	£ ha^{-1} per harvest	219	141
Storage Cost	£ ha^{-1} per harvest	42	23

Variance and covariance matrix. A matrix of variance and covariance was generated to encapsulate the associated levels of uncertainty and correlations between activities, and used to calculate the total income standard deviation for sets of activities. The variances and covariances were calculated from historical data over the period from 1990 to 2010, using DEFRA (2011a) data. Although this is likely to underestimate the variance, as the data are already averages (Freund, 1956), insufficient data were available to use a disaggregated set of values. The variances and covariances were calculated in income terms, as it was assumed that the uncertainties of input costs were relatively small.

Energy crops variance and covariance. No suitable direct historical data series were available to determine an estimate of uncertainty in the energy crop price. Energy crop prices are believed to be strongly correlated with the oil markets (Song *et al.*, 2010), therefore fuel oil price data were chosen to generate an energy crop price variance index (DECC, 2010). An estimate of yield uncertainty was generated using the standard deviation of yields in field trials for *Miscanthus* (Richter *et al.*, 2008). The price and yield variances were combined to provide an estimate of the indexed energy crop income variance, assuming that they were uncorrelated (Barnett, 1955). The indexed variances and covariances were rebased using the expected energy crop income for each scenario being optimized. Decision-makers may choose to be more conservative with respect to their assessment of energy crop uncertainty. To represent this, a factor was applied to the energy crop variance. This factor can be considered to represent the additional risk or the perception of it. As per Alexander & Moran (2013), a factor of 1.5 was chosen as the central figure, implying approximately a 22% increase in the resultant energy crop standard deviation.

Farm-scale model validation. Validation was done to observed conventional crop data, due to lack of sufficient empirical data for energy crops with the lowest net difference occurring at a risk aversion of $\phi = 0.35$ (Alexander & Moran, 2013). This is within the range previously used or imputed for other farm models using this representation of risk (Brink & McCarl, 1978; Hazell & Norton, 1986; Semaan *et al.*, 2007) and within the range which behaviour was investigated. Alexander & Moran (2013) give further details of the farm-scale model construction, validation and sensitivity analysis.

Relative energy crop price

The low heating value (LHV) was used to provide a consistent price for biomass energy from each energy crop. LHV, also known as net calorific value, is the energy released on combustion after the water contained in the fuel has been vaporized. *Miscanthus* was assumed to have a moisture content of 15% and an LHV of 15.1 GJ t^{-1}, while the SRC willow was taken as having 30% moisture, after a period of natural drying, with an LHV of 12.1 GJ t^{-1} (Hillier *et al.*, 2009). To allow comparisons or unbiased setting of the energy crops prices, the LHV of each crop was used to convert between crop prices and biomass energy prices. The lower LHV value of SRC willow, due partially to higher moisture, implies a lower market price in comparison to *Miscanthus*. Taking a market price for *Miscanthus* of £60 odt^{-1} in 2010 terms (NNFCC, 2010a; Sherrington & Moran, 2010), the LHV figures imply an expected SRC willow price of £48 odt^{-1}. This figure falls in the range of previously estimated market prices for SRC willow, which was £40 odt^{-1} (Aylott *et al.*, 2010; Sherrington & Moran, 2010) to £50 odt^{-1} (NNFCC, 2010b). The remainder of the paper will use £60 odt^{-1} and £48 odt^{-1} for *Miscanthus* and SRC willow respectively as estimates of current market prices. Where other prices are used, the relationship between the prices of these crops is maintained, such that, the price per net calorific energy is equal. All prices are in 2010 terms unless otherwise stated.

Spatial configuration

The farm-scale model behaviour displays highest sensitivity of energy crop area selected to the yields of conventional crops and energy crops (Alexander & Moran, 2013). Therefore, to generate an improved understanding of the potential economic supply of energy crops, variations in yields need to be included in the analysis. Crop yields will differ by site location, through variation in soil, climate and topography. Therefore, a spatially disaggregated methodology is required to include yield variability. Such an approach allows the selection of energy crops to occur on sites where relatively low conventional crop yields are coupled with relatively high energy crop yields, contributing to more favourable expected energy crop returns. Distributions of yields across the United Kingdom for all the activities in the farm-scale model are needed to configure farm representations for each location. Constraint masks were required to limit the selection of sites to those likely to be deemed acceptable for energy crop growth from a social and environmental perspective, and to locations where demand for them could exist. A regular 1 km^2 grid was chosen, where each grid square was considered an independent 100 ha farm, and optimized as such. This resolution provides sufficient spatial detail to capture climate and large-scale soil variation, and was in line with the resolution of some of the yield inputs. It also provided a relatively realistic farm size, compared to the average UK farm size of 57 ha (UK Agriculture, 2013), and was computational tractable.

Where required, the input data used were resampled to ensure a consistent coordinate system and grid size. More details on the data sources for each crop are given below. A Java programme was developed using the Java Development Kit 7 (Oracle, 2012) to read the various input distributions, collectively allowing the farm model input data for each location to be determined. Rather than directly optimizing each case, only unique cases are optimized by identifying all cases that have duplicate input values. In this way, the data for all locations with the same values can be handled by a single farm-scale model execution. Once the unique cases have been identified with the mapping from the location to the unique input data, the programme creates and executes the GAMS models for all the unique cases. The outputs of these optimizations are then associated with all the relevant locations to obtain a complete representation of all activities within the area studied. The data can then be output in various forms for further analysis.

The steps involved in the model execution can be seen in Fig. 1, breaking each stage down further, they can be summarized as follows:

Stage I – Input Marshalling

1. Reads all the input data, including yield data, scenario data, etc.
2. Determine the set of unique cases.
3. Create GAMS model for each unique case
4. Create mapping from raster cell to one of these model case.

Stage II – Optimization

5. Executes each model in GAMS.

Stage III – Results Processing

6. Use farm-scale model outputs and the raster cell to model case data and creates output data files and images of the output data.

Conventional crop yield distributions. Although spatially disaggregated yield data for conventional crops would be highly desirable, no source of such data was available, so regional yields were used (DEFRA, 2011b; Scottish Government, 2011; Welsh Government, 2011). The data for Wales relate to 2009 while other data are for 2010. The regional yield data for England and Wales provided an aggregate figure for barley for each region, without the distinction between winter and spring sown crops. To provide a regional yield estimate, winter and spring barley figures were divided using for the mean Scottish proportions, prorated to maintain the regional averages. No regional yield data were available for Scotland for sugar beet, peas or beans so the figures from North East England were used. Similarly, West Midlands figures were used for oilseed, sugar beet, peas or beans for Wales as these figures were not available in the Welsh Government data set. To define the location of the regions, the OS boundary data were used (Ordnance Survey, 2011). The resultant yields maps for a sample of the key conventional crops are shown in Fig. 2.

Energy crop yield distributions. *Miscanthus* yield distributions were obtained from Hastings *et al.* (2014). These results were generated from the MISCANFOR model with UKCP09 climate data (Murphy *et al.*, 2009) and soils data from the harmonized world soil database (FAO/IIASA/ISRIC/ISSCAS/JRC, 2012) to estimate a peak yield over the United Kingdom using a 100×100 m grid. Peak yield estimates were scaled by 0.67 to obtain harvestable yield after senescence and drying the following spring (Hastings *et al.*, 2014). The model was used to obtain yield estimates for each climate change UKCP09 scenarios. The resultant 100×100 m raster data were resampled in ArcMap to a 1 km^2 grid coordinate system. SRC willow yield distributions were obtained from Tallis *et al.* (2013). To ensure consistency of results, the same soil and climate data were used. The SRC willow yield modelling was executed using a 1 km^2 grid over the range of climate change scenarios. The results for both the *Miscanthus* and SRC willow yield distributions for the 2010 climate baselines are shown in Fig. 3. The changes to these yields under high emission climate scenarios for 2020, 2030 and 2050 are shown in Fig. 4.

Constraints. Not all areas will be available for potential perennial energy crop growth, regardless of whether or not they may be economically grown at that location. Also, as transportation costs are high due to the low energy density, a local demand is needed. To exclude areas that would not be appropriate, two distinct types of land-use restrictions were applied to constrain the selection; a set of social and environmental constraints, and a demand constraint.

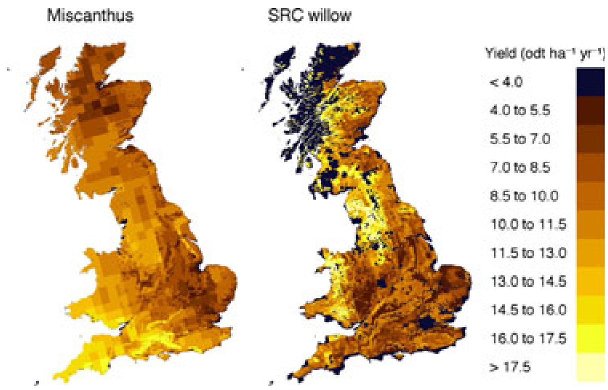

Fig. 3 Unconstrained energy crop yield maps for baseline (2010) climate scenario for *Miscanthus* and SRC willow (sources: Hastings *et al.*, 2014).

Social and environmental constraints. Social and environmental constraints restrict the areas that would be available to grow these energy crops. Lovett *et al.* (2014) produced a mask of areas which would be unavailable based on 8 factors, these removed areas that were road, rivers and urban areas; slope > 15%; monuments; designated areas; existing woodlands; high organic carbon soils; and areas assessed as having a high 'naturalness score'.

Demand constraints. Wang *et al.* (2014) produced a distribution for the United Kingdom of economic energy crop demand given transportation costs to locations where heat and electricity demand may exist. The model is able to exogenously specify land competition percentage to constrain the area available for energy crops. The supply-demand model of Wang *et al.* (2014) provides estimates of where energy crops could provide cost-effective supply of heat and electricity, but does not consider farm-scale economics determining whether

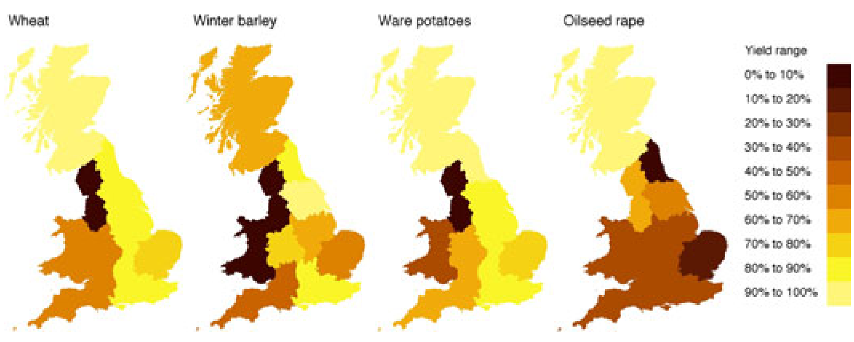

Fig. 2 UK yield comparison maps of sample conventional crop, based on regional yield data for wheat, winter barley, ware potatoes and oilseed rape, showing variation between maximum and minimum yields for each crop (source: DEFRA, 2011a; Scottish Government, 2011; Welsh Government, 2011).

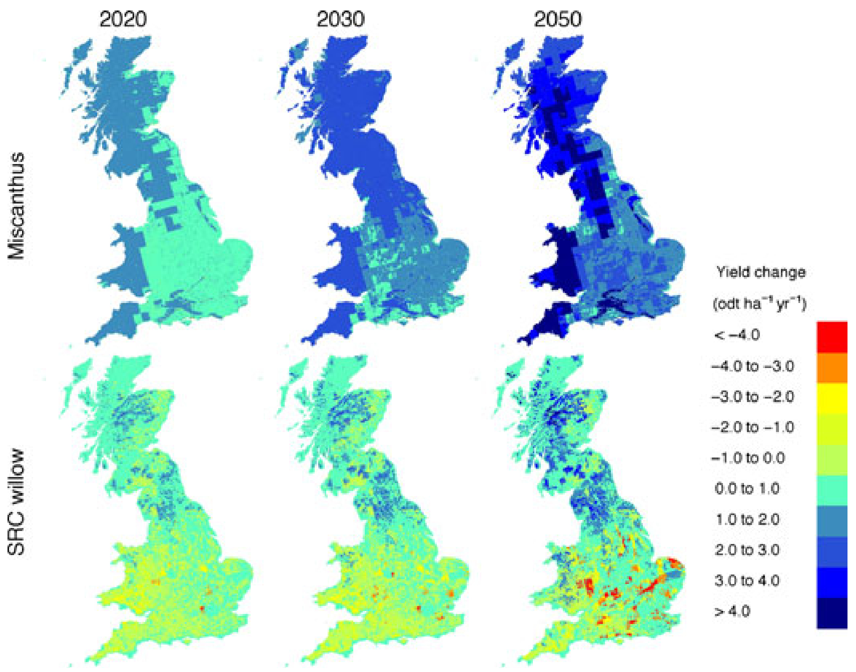

Fig. 4 *Miscanthus* and SRC willow yield change maps from baseline (2010) climate scenario to 2020, 2030 or 2050 using high emission scenario (sources: Hastings *et al.*, 2014).

farmers will decide to plant energy crops rather than conventional crops. For this, the farm-scale model described here is used, to represent competition for land, and to limit the area use for energy crops, by assuming that the farmers' economics provide an appropriate mechanism for the efficient allocation of land resource. The areas found to be unsuitable for energy crop production to supply electricity and heat to areas of demand by Wang *et al.* (2014) were excluded. A map showing these two constraints can be seen in Fig. 5. The areas available for potential selection of energy crop were restricted using the aggregate of these two constraint masks.

Yields under climate change scenarios

The modelling of responses to climate change scenarios required yield estimates for all crop activities under each scenario considered. The impact of such changes will vary spatially, so an approach to assessing the impact that takes account of variation by location was required. Butterworth *et al.* (2010) looked at effect of climate change on oilseed rape yields. They estimated the adjustment to these yields at a regional level for England and Scotland using UKCIP02 (Hulme *et al.*, 2002). The treated oilseed rate percentage adjustments results were used for all climate scenario conventional agricultural crop variations. The data for Wales were unavailable so the results for West Midlands were used for that region. The energy crop yield distribution were produced under the UKCIP09 climate scenario by Hastings *et al.* (2014) and Tallis *et al.* (2013). After the same resampling process as described for the baseline case, these were input into the spatial model allowing the supply curves and distribution to be generated for each climate change scenario.

Results

Baseline UK energy crop supply

UK aggregate supply. The UK supply curves for these perennial energy crops were generated by running the model with a range of *Miscanthus* and SRC willow prices. A farm plan, giving the optimum level of all activities, was generated for each 1 km^2 farm, farm-gate price and climate scenario. A point on the supply curve was found by summing each value for each energy crop across a given geographic area for that farm-gate price

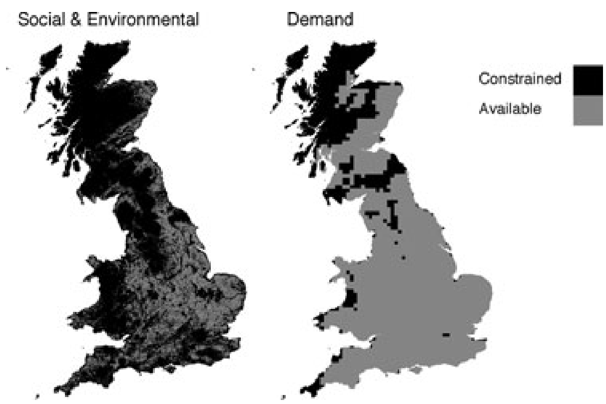

Fig. 5 Social & environmental and demand constraint maps for energy crops (sources: Lovett *et al.*, 2014; Wang *et al.*, 2014).

and climate scenario. The separate energy crop prices were adjusted using the LHV to maintain a consistent usable biomass energy price from combustion. Supply can be expressed in terms of area used for crop production, supplied mass or supplied energy. Figure 6 shows the UK supply curve for the two perennial energy crops in terms of mass supplied per annum. The scales of the *Miscanthus* and SRC willow price axes have been chosen so that the price per net calorific energy is equal. Examining the annual supplied mass, at low supply amounts then SRC willow dominates the mix of energy crops. SRC willow accounts for 94% of the economic energy crop area at a SRC willow price of £32 odt^{-1}, the *Miscanthus* LHV equivalent price is £40 odt^{-1}. At higher supply rates and correspondingly higher prices, *Miscanthus* accounts for an increasing proportion of supply. At an estimate of current market prices of £60 odt^{-1} for *Miscanthus*, 70% of energy is supplied from that crop, from 65% of biomass using 66% of the area selected. The dominance of *Miscanthus* in the economic supply of biomass from perennial crops increases further with higher prices and supply rates, at a price of £80 odt^{-1}, 79% of the energy is from that source.

Regional variations of supply. The UK supply curve loses the spatial variability of the results. The low energy density of these energy crops results in a high cost of transport (Borjesson & Gustavsson, 1996), making the distribution of the supply an important consideration. To provide a visualization, Fig. 7 shows the rate of area selected for both energy crop mapped across the United Kingdom, using currently estimated market prices and baseline climate data. These maps of economic energy crop selection demonstrate that both crops do have highly regionally specific behaviours. The South West region of England appears to dominate *Miscanthus* selection, while the North West region dominates SRC willow selection.

To quantify the regional differences in behaviour, the supply was aggregated at that level. Again taking a price of £60 odt^{-1} for *Miscanthus*, and the LHV equivalent price of £48 odt^{-1} for willow SRC, shows that 52% of UK *Miscanthus* supply mass is from the South West of England and 85% of SRC willow supply is from the North West of England, produced from areas of 85 000 ha of *Miscanthus* in the South West and 77 000 ha of SRC willow in the North West of England. Under this scenario, a total area of 260 000 ha was selected for energy crops. Table 2 shows these and the other regional figures for the United Kingdom, including supply expressed in area, mass and energy terms and the mean yields for each area. Figure 8 shows the supply curves by mass aggregated at a regional level for *Miscanthus* and SRC willow, again demonstrating the highly regionally specific behaviour.

To provide an indication of the relative ability of each energy crop to act as a substitute, and whether there was direct competition for the select on the same land, the model was also run with selection of each energy crop suppressed in turn. The results of these runs were compared against optimization where both energy crops were available (Fig. 9). As expected the aggregate supply is greatest where both crops are available for optimization. However, the reduction in supply by removing the option to select SRC willow is relatively small at high supply rates. For example at £90 odt^{-1} *Miscanthus* price, the reduction in aggregate energy supply is 12%, by removing the option to select SRC willow. At the equivalent price of £72 odt^{-1} SRC willow price, the aggregate is reduced by 62% by the suppression of *Miscanthus* and allowing only SRC willow selection.

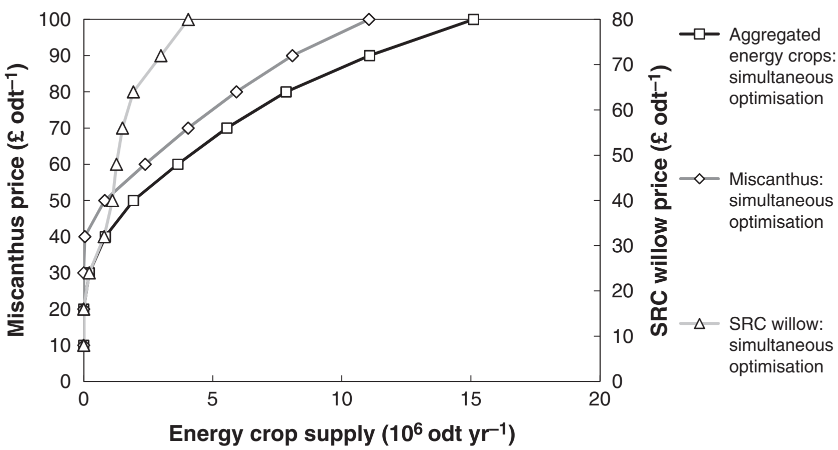

Fig. 6 *Miscanthus*, SRC willow and aggregate supply mass for the United Kingdom using baseline data, with energy crops optimized simultaneously.

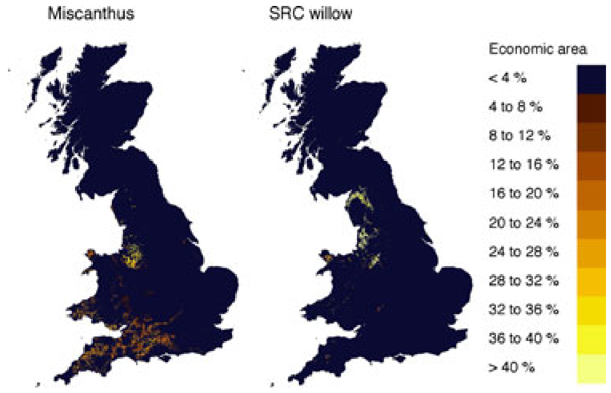

Fig. 7 Economic energy crop supply distribution maps, optimized concurrently, using the baseline scenario at current market prices for *Miscanthus* (£60 odt^{-1}) and SRC willow (£48 odt^{-1}).

Climate change impact on supply

The model was run using yield estimate distribution under various climate change scenarios. The supply curves from the baseline and low emission scenarios are shown in Fig. 10. Climate change reduces the economic area of SRC willow, with the effect increasing as climate changes into the future. The opposite impact is seen with *Miscanthus*, with the baseline case producing the least economic area for a given price. The impact for SRC willow is greater and more systematic in comparison to that of *Miscanthus*. The SRC willow area decreases over time, while the *Miscanthus* area decreases initially, until 2020, and then remains broadly static. There are significant regional and crop variations in adjustment to climate change, making generalization difficult. To separate what level of change resulted from energy crop adjustment and that resulting from the conventional crop adjustments, the model was run with no adjustment made for conventional crops. The results show the same directional change as shown in Fig. 10, but the response for SRC willow was lower, and that for *Miscanthus* was greater. The *Miscanthus* response to climate change also increased over time. Figure 10 also shows the results from all 2030 climate scenarios, with similar behaviour noted under the 2020 and 2050 scenarios.

Risk aversion sensitivity

The sensitivity to the risk aversion parameter over the range of 0.0–2.0 was determined by running the model for the baseline case with a range of risk aversion parameters. Figure 11 shows supply curves of the economic area for *Miscanthus* from runs with *Miscanthus* optimized only. As an indication of sensitivity to the risk aversion parameter, the price that provides an economic area equal to the target area of 350 000 ha (DEFRA, 2007) was determined. This was done by linear interpolation between the two price points either side of the target area. Table 3 shows the required prices and the percentage change in price from the central estimate of a risk aversion of 1.0.

Both Figure 11; Table 3 suggest that the total supply does not show a particularly high sensitivity to the risk aversion parameter in the range 0.0–1.5. The reason for this appears to be that two opposing effects occur with adjustments to risk aversion. As risk aversion reduces, the number of farms that select energy crops decreases, but a significant reduction in supply does not occur as it is counteracted by an increase in selection rate at those farms that do select. At very high risk aversions, above 1.5, the incentive to diversity increases, as the risk component starts to dominate. So at lower energy crop

Table 2 Regional supply quantities and mean yields at a *Miscanthus* price of £60 odt^{-1} and an SRC willow (SRC) price of £48 odt^{-1}

Region	*Miscanthus* supply 1000 odt yr^{-1}	SRC supply 1000 odt yr^{-1}	*Miscanthus* area 1000 ha	SRC area 1000 ha	Mean *Miscanthus* yield odt yr^{-1}	Mean SRCW yield odt yr^{-1}	*Miscanthus* energy PJ yr^{-1}	SRC energy PJ yr^{-1}
East Midlands	2	1	0	0	14.1	17.0	0.03	0.01
Eastern	2	0	0	0	15.1	–	0.03	0
North East	0	3	0	0	–	16.4	0	0.04
North West	413	1083	34	77	12.0	14.1	6.29	13.11
Scotland	0	3	0	0	–	17.1	0	0.04
South East	258	0	16	0	15.9	–	3.92	0
South West	1235	37	85	3	14.6	14.7	18.78	0.45
Wales	427	117	31	8	13.7	15.4	6.49	1.42
West Midlands	36	8	3	1	12.2	14.2	0.55	0.09
Yorkshire & Humber	7	16	1	1	13.8	16.8	0.11	0.19
Total	2380	1268	172	89	14.0	14.2	36.20	15.34

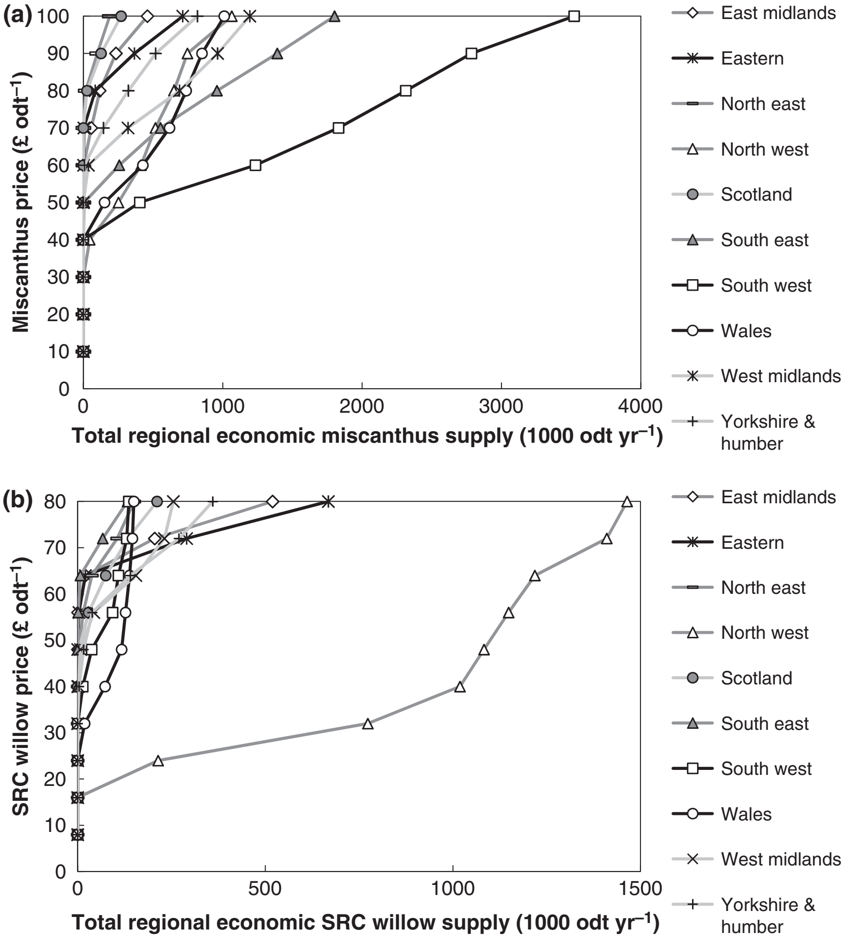

Fig. 8 Regional breakdown of (a) *Miscanthus* and (b) SRC willow supply curves for the United Kingdom using baseline data, optimized simultaneously.

prices, the selection is increased in comparison to the scenario of low risk aversions; farmers are more willing to take a lower profit for a reduction of risk. At higher prices lower uptakes are seen, as the preference is still to keep a diversified crop selection, though at these prices, *Miscanthus* often has the highest gross margin.

Discussion

The model outputs give an indication of the amount and distribution of *Miscanthus* and SRC willow crops that could be economically grown at a given farm-gate price for biomass energy. These results cannot be seen as a prediction of farmer's uptake of these crops under a given scenario, as many other factors are involved that limit uptake and act to constrain it, for example attitudes to novel crops and distances to an available market. Despite this, the results do suggest a potential maximum limit on uptake, as crops are unlikely to be widely grown where they are not economic in comparison to alternative activities. Some of the factors that may be involved in restricting the selection of these energy crops are: the availability of a market which they can be sold, the distance to these markets, and farmer's willingness to choose an innovative crop. These factors would be expected to diminish in possible significance as the size and spatial reach of the market increases.

The input data used for conventional crop yields and climate change adjustments are not considered ideal. Due to lack of higher resolution data, the baseline conventional crop yields are from regional data, while the energy crops have yield estimates at a 1 km^2 scale. This may create a positive bias for the selection of energy crops in some regions and a negative bias in others. In regions with relatively low average conventional crop yields, a bias may result towards selecting the better quality sites for energy crops, as the yield predictions for the energy crop are able to take this into account while the regional mean yields on conventional crops cannot capture that variation. However in the regions with high mean conventional crops yields, this is reversed, with relatively poor yielding areas, that may

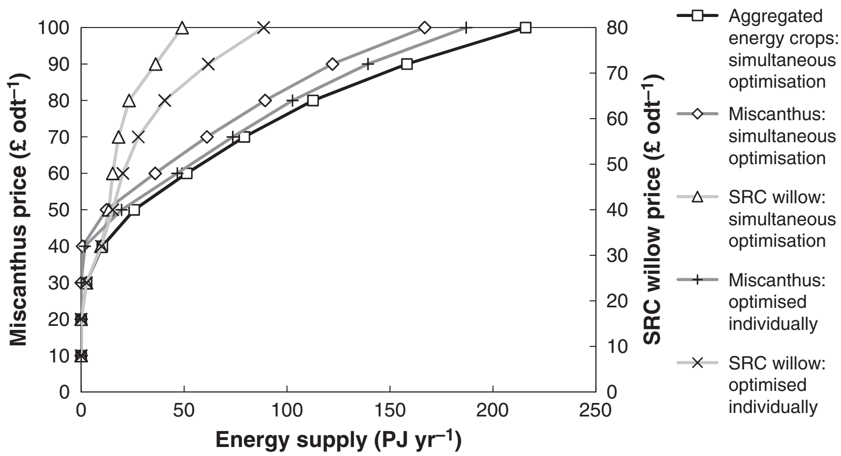

Fig. 9 Energy supply for the United Kingdom from energy crops, using optimizations with *Miscanthus* only, SRC willow only and both energy crops simultaneously.

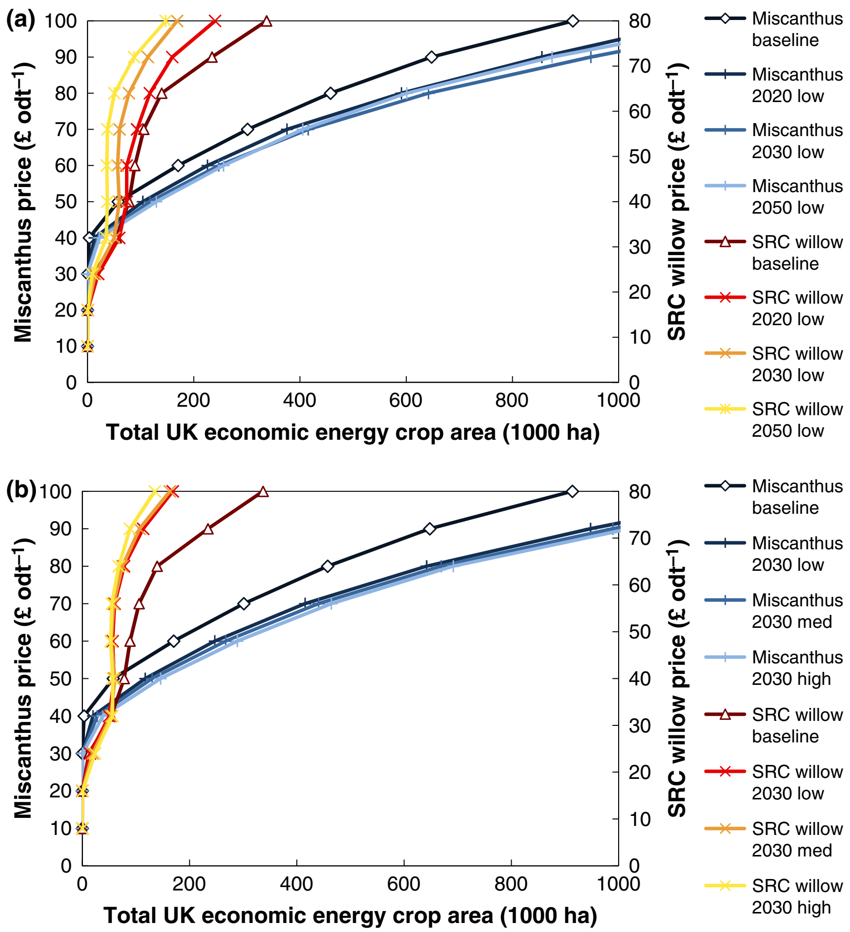

Fig. 10 The UK total perennial energy crop supply curves (a) under 2020, 2030 and 2050 low climate change scenarios, and (b) under high, medium and low emission scenarios for 2030.

be suitable for energy crop selection, potentially failing to be selected, hence creating a negative bias. Differences in biophysical growth properties of the crops may reduce or remove such an affect. It is difficult to quantify the impact of these effects without having a more disaggregated set of conventional crop yield data over

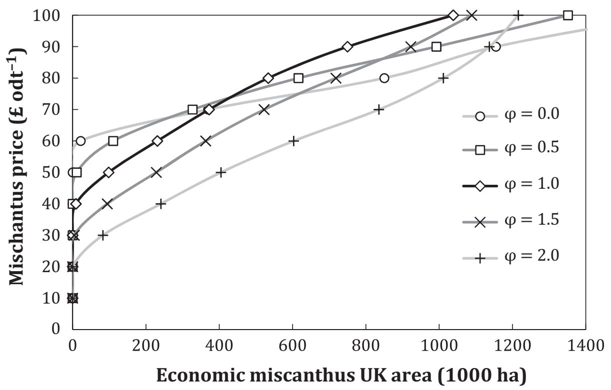

Fig. 11 Sensitivity of economic UK area for *Miscanthus* to variations in risk aversion parameter.

which to run an analysis. The regional yield data come from three sources (Defra, Welsh Government and Scottish Government), which may lead to inconsistencies in methodologies or data gathering approaches. Furthermore, the data for Wales were for the 2009 harvest, while other regions were for 2010, due to lack of published data for that year for Wales.

Another issue with the conventional crop yield data relates to using the OSR climate adjustment factors for all conventional crops. This is an approximation borne of the lack of factors for each crop. Comparing the results using these adjustments and where no conventional crop adjustment shows that in areas important for energy crops production, the conventional crop adjustments provide a net increase in yields. However, this is smaller than the net increase in the yields for *Miscanthus*. In the case of the SRC willow, the response to climate change is negative, while the conventional crop adjustment tends to increase yields, which generates a greater reduction in SRC willow selection. Despite some concern about the conventional crop adjustments used, the response to climate change for each crop is clear, and that the response is greater than that predicted for OSR.

The assessment of risk of a portfolio of crops is calculated using variance and covariances calculated from a historical data set over a 20 year period, assuming the energy crop prices correlate with oil prices (Alexander & Moran, 2013). It has been suggested (FAO, 2008) that arable prices have become more correlated with oil price, although there is evidence of a complex relationship (Nazlioglu, 2011). If the historical data underestimate farmers' perception of these price correlations, then the model will also underestimate the farmers' expected correlation between energy and arable crop incomes. In situations where energy crops have a lower expected gross margin, the result would be a bias towards lower modelled economic energy crop area, as the modelled incentive to diversify with these crops is reduced. Where the energy crop has a higher gross margin the opposite effect would occur, because similarly the incentive to maintain a diverse set of activities using arable crops is also reduced.

The costs of agricultural activities have been modelled using contractor rates, but many farm business use on-farm labour and machinery, which may form a barrier to energy crop adoption (Sherrington *et al.*, 2008). There are a number of reasons to believe that this cost assumption will not significantly impact the results presented here. Firstly, a relatively large change in labour and machinery costs is unlikely to influence the results significantly, as the cost of labour and machinery is only a proportion of total input cost (39% for wheat), and the farm-scale model is less sensitive to input costs than to crop yields or prices (Alexander & Moran, 2013). Secondly, if farm labour or machinery becomes available due to switching of cropping activities then these can be made use of off-farm, for example by conducting contracting work for other farms [14% of holding in England already are involved with some form of contracting or haulage (DEFRA, 2012)], or selling of redundant machinery. Thirdly, such issues only form a transient barrier to adoption that is not represented by this analysis. Another potential issue is the inclusion of sugar beet in the potential agricultural activities, without constraints to only selecting areas where processing facilities exist. However, the low sugar beet uptake (Alexander & Moran, 2013) suggests that it is unlikely to materially affect the results.

The UK Biomass Strategy identifies the prospect of part of the increased supply coming from a major expansion of UK production in perennial energy crops, potentially using 350 000 ha, an area equivalent of 6.5% of total arable land (DEFRA, 2007). Linearly interpolating between results, to obtain an economic area of this scale in aggregate between these crops requires a price of £66 odt^{-1} for *Miscanthus* and the equivalent price of £53 odt^{-1} for SRC willow. These prices are somewhat

Table 3 *Miscanthus* prices required to provide 350 000 ha of economic *Miscanthus* selection for a range of risk aversion parameters (ϕ)

	ϕ = 0.0	ϕ = 0.5	ϕ = 1.0	ϕ = 1.5	ϕ = 2.0
Miscanthus price (£ odt^{-1})	£69.44	£70.79	68.41	59.03	46.66
Change from baseline ϕ = 1.0 (%)	1.5	3.5	–	−13.7	−31.8

higher than current market levels, around 8% in both cases. However, the actual uptake has been comparatively limited, at around 17 000 ha (RELU, 2009). Although this figure is somewhat out-of-date, more recent figures from Natural England suggesting that no increase in the rate of planting has occurred subsequently; in fact their data imply a reduction in the rate of establishment. During the period 2000–2006, grants to establish a combined area of 8191 ha were provided in England, while in the period 2007–2011 only 1305 ha received establishment grants (Natural England, 2006, 2011).

The results show that SRC willow dominates the mix of energy crops at a low energy crop price, but that with higher prices *Miscanthus* accounts for an increasing proportion of supply, and at a sufficiently high price the majority of supply is provided by *Miscanthus.* The *Miscanthus* area as a percentage of the total energy crop is just 6% at a *Miscanthus* price of £40 odt^{-1}, but increases to 76% at £80 odt^{-1}. The reason is that there is a small area of SRC willow estimated with very high yields (>17.5 odt ha^{-1} yr^{-1}), located mostly in the North West of England (Fig. 3). These areas coincide with relatively low cereal yields (Fig. 2), and so are selected by the farm-scale model at relatively low crop prices, down to £24 odt^{-1} for SRC willow where 12 000 ha is economic. However, these areas are relatively limited and once they have been selected, the SRC willow yields on the remaining areas quickly reduce. *Miscanthus,* on the other hand, has no areas with such high yields predicated, but a greater area with a more moderately high yield (>14.5 odt ha^{-1} yr^{-1}). It also has the advantage of a higher crop price, with relatively similar establishment costs, in comparison to SRC willow. As a result, at a sufficiently high price for *Miscanthus* to become economic in these areas, a greater uptake is supported.

The results suggest that at a UK level SRC willow is only likely to able to supply a small proportion of the anticipated perennial energy crop target, without increases in market price. The economic area for SRC willow calculated, acknowledged to be a ceiling on actual uptake, does not reach the target until over a price of £80 odt^{-1}, nearly double current market levels. Actual uptake will, as previously discussed, be further limited by other considerations. *Miscanthus* appears to have greater scope for supply, to have an economic area for production equal to the target requires a price of £73 odt^{-1} a 22% rise from current market levels. The rate of increase in economic areas to a rise in market price is also greater for *Miscanthus* than SRC willow, above £40 odt^{-1}. The different impacts of climate change on each crops (Fig. 10) further suggest the likely larger role for *Miscanthus* than SRC willow.

The impact of climate change, under all emission scenarios, is to significantly reduce the economic supply for SRC willow, even by 2020 (Fig. 10). At current market levels, the area of SRC willow is reduced to just 41% of baseline levels under the low emission 2050 scenario, and only 32% in the high emissions scenario. Even in the 2020 low emission scenario, a reduction to 83% of the baseline level results. The rate of reduction increases with higher biomass prices. In contrast, the supply *Miscanthus* increases under all climate scenarios. At 2050, a 50% and 47% increase in selected area from the baseline is seen under the low and high emission scenario respectively, at current market prices. The 2020 low scenario has a 34% increase. The aggregate results in an approximately 10% rise in total energy crop selected area in each of these scenarios. These changes are being driven by the relative yield change in the energy crops and the other agricultural activities. Figure 4 demonstrates that the impact of climate change on the two energy crops is complex, but broadly the *Miscanthus* yields are increased, with many areas having substantial gains (>4 odt ha^{-1} yr^{-1}). SRC willow has a more mixed picture with limited areas seeing increases, and most areas having reduced yields. In all climate change scenarios, SRC willow supply is reduced and *Miscanthus* is increased, suggesting that the initial dominance of *Miscanthus* may be amplified over time.

At current market prices, the indicated economic area is 260 000 ha. Taking the current area as 17 000 ha (RELU, 2009), this implies that only 6.5% of economic sites are actually being selected to grow the crops. There are many reasons that have been postulated for why uptake has been slow (Sherrington & Moran, 2010). The model presented here includes a risk model to provide some representation of this aspect; however, it does not attempt to include either the barrier to adoption of the innovation that these crops represent or the lack of a market into which farmers can sell their production. Adoption of previous novel crops has shown long time lags, despite an apparently positive economic case. For example, the adoption of oilseed rape show time lags of 15–20 years when the price of oilseed rape stabilized and increased due to the intervention price structure after United Kingdom entered the European Economic Community in 1973 (Wrathall, 1978; Allanson, 1994; EDINA, 2012). The adoption over the following 25 years displays the typical S-shaped curve of a diffusion of innovation process (Rogers, 1995). Such time lags suggest that adoption and diffusion of innovation behaviour may be important for the update of energy crops. An additional issue with these crops is that without a readily available and accessible market, there would seem little likelihood that the crops will be established. The relatively low energy density of these crops exacerbates the issue, as it means that transportation costs are high and so that economic distances that the material can be transported are commensurately low (Borjesson & Gustavsson, 1996). Local demand is therefore needed into which the produced crops can be delivered at a viable cost (see Wang *et al*., 2014). The low level of uptake suggests that efforts to encourage market development may be important in meeting the aspiration for UK energy crop growth. The 'chicken and egg' problem appears as significant barrier, where farmers are not willing to grow the crops without a more mature market and potential investors are not willing to develop the plants and technologies that are required to create the demand and so establish the market (Sherrington *et al*., 2008). The cyclic contingent behaviour between farmers and plant investors increases the complexity of the overall system, making analysis more difficult.

A high degree of regional concentration in supply is demonstrated by the results; see Table 2; Fig. 8. The distribution of energy crop selection appears primarily due to the relatively high energy crop yields, tempered by the yields on the other agricultural activities. Figure 3 shows that many areas of high SRC willow yields are in Wales and the North West of England. However, most of these areas in Wales are unavailable due to the socio-environmental constraints (Fig. 5). The result is the North West of England leads the supply of this crop, with 85% of supply at assumed prices. Other regions do not have many areas with yields high enough to allow the returns for this crop compete with the returns of the other crops. The relatively high yielding areas for *Miscanthus* (>14.5 odt ha^{-1} yr^{-1}) are focused around the South West of England, but extend north and east. The economic areas for *Miscanthus* also include areas where the yields on that crop are not quite as high (between 11.5 and 14.5 odt ha^{-1} yr^{-1}), primarily in the North West of England. These areas appear to be economic due to the relatively lower yields on conventional crop activities; however it remains in the South West of England providing the majority of supply (52% at £60 odt^{-1}).

The regional concentration in supply may be beneficial with regard to creating the conditions required to establish locally viable market for these crops, in the regions where significant economic supply exists. The high transportation costs make small supply distances desirable, both from a financial and GHG standpoint. However, sufficient supply is required to make construction of facilities to consume these crops for direct power generation or pelletization, implying benefits in having locations where there is a high density of land used to produce the crops. More work is needed to understand the dynamics between the distribution of supply and the potential locations of plants. Such work would address deficiencies in the current analysis, allowing further insights to be gained into the barriers that limit the market development. For example, the current model limitation on having a homogeneous farm-gate price would be addressed, by determining and accounting for the cost for transportation between supply and demand locations. A dynamic model that supports the representation of market growth, including out of equilibrium market conditions would also be required to study the potential patterns of growth and the factors that influence it. Modelling of a market with contingent behaviour can be problematic with traditional methods and the spatial aspects of the system further increase the complexity. An agent-base modelling approach may be suitable as it has previously been used to dynamically model other spatial systems with contingent behaviour (Dibble, 2006).

These results suggest *Miscanthus* has a higher rate of potential economic supply, in comparison to SRC willow, implying that it may be a more significant crop in the production of biomass. The response to climate change scenarios further favours *Miscanthus*, suggesting that *Miscanthus* supply increases under future climate, while SRC willow supply is expected to reduce. The economic areas using current market prices are far in excess of crop uptake to date, suggesting that significant barriers to market adoption may exist, potentially involving the lack of farmers' access to a local market for the crop. Highly regional specific behaviour was noted, which may assist market development within areas with the highest concentration of potential economic supply. To understand the dynamics of the interaction of farmers choosing to grow the crop, and investors choosing to build the consuming plants, further modelling work is required to represent the behaviour of the market as a whole.

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